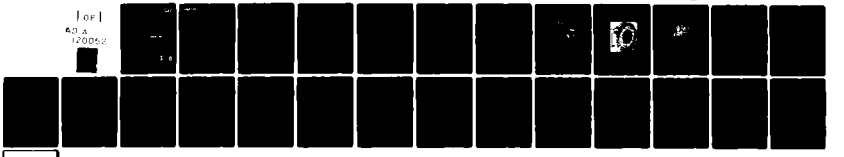
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PERFORM EXPERIMENTS ON LINUS-0 AND LTX IMPLODING LIQUID LINER FUSION SYSTEMS

JAYCOR Report Number J206-82-012/6203

August 27, 1982

FINAL REPORT

by E. P. Scannell

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I. INTRODUCTION

The Plasma Physics Division of the Naval Research Laboratory (NRL) has been conducting investigations of imploding liquid liner fusion systems for several years (Reference 1). This effort attained a significant milestone in 1978 with the construction of two machines: HELIUS and LINUS-0. LINUS-0 is a 60 MJ rotor system where a cylindrical liquid sodium - potassium (NaK) metal liner is radially compressed from a 30 cm to 1 cm diameter by gas pressure from multiple high explosive charges. These charges act on an annular piston in contact with the liquid NaK liner material. HELIUS is a half-scale vertical axis version of LINUS-0 using high pressure helium to drive the annular piston. HELIUS is designed to be a test bed for new concepts and to permit testing of new modifications to LINUS-0. The principal virtue of HELIUS is its capablilty for ten to twenty shots per day as compared to two or three shots per day for LINUS-0. In addition, HELIUS is designed to provide higher drive pressures than were previously obtainable with water models for liner hydrodynamic studies and a magnetic flux compression capability up to $\sim$ 100 kG.

The LINUS-0 design was sized to provide sufficient high energy densities in the imploding liquid metal liner to compress the initial magnetic fields to levels of $\gtrsim$ 250 kG. At these levels nonlinear magnetic diffusion is observable. The system radius is a function of magnetic diffusion efficiency. At these energy densities, LINUS-0 will permit reasonable comparisons to be made between theoretical and experimental results. These comparisons provide bench mark data in the parameter range of interest for reactor scaling and the design of future LINUS plasma compression experiments (LPX).

The work to be performed by JAYCOR during this reporting period was in two principal areas:

- Instrumentation of the LINUS-0 machine with accelerometers and investigation of impulse loading on tne LINUS-0 machine.
- Assemble and conduct initial experiments on the hydrodynamic water model system to test the implosion dynamics of a tangentially injected liner into a non-rotating housing (LTX).

These two areas of work were partially completed when the NRL program changed emphasis. The new areas of work for the JAYCOR effort were:

- Completion of the documentation, disassembly and storage of the LINUS-0 and HELIUS devices.
- Maintain equipment for and conduct a high power demonstration of the NRL homopolar generator (HPG) inductive load system.
- Conduct an electromagnetic pulse (EMP) simulation demonstration using the NRL HPG/inductive storage system.
- Design, assemble and test various plasma switch components using plasma guns.

The LINUS-0 and HELIUS devices were disassembled and placed in storage areas. All documentation concerning the devices was submitted to the COTR. The remaining work areas, including those before the change in program direction, are discussed in the following sections.

II. LINUS IMPLODING LIQUID LINER EXPERIMENTS

A cut-away drawing of the LINUS-0 device, with its modified annular piston design is shown in Figure 1. Figure 2 is a photograph of one rotor half, with the original piston design installed, showing the twelve guide rods in the original position. Figure 3 shows a cross-section of the LINUS-0 (explosive) charge box and rotor seal area, as well as the positioning of the guide rods in the rotor guide rod holes. These figures are necessary to visualize the location and application of the various transducers used to study the mechanical loadings.

Pressure transducers were placed in some of the charge boxes in front of the explosive chamber shown in Figure 3, the plugged guide rod holes, to read piston drive pressure, and in the movable, shock-absorbing windows near the hollow rotor axis. The latter is shown in Figure 1 as the circles on the left end plate, or slug, with the dashed lines indicating connecting cables. Figure 1 shows a thick optical window in the right-hand side end plate position to indicate the primary purpose of the hollow axle of the LINUS-0 rotor. The purpose was to have an optical window serve as the shock-absorbing end plate on both ends, thus allowing optical diagnostics of the liquid liner's imploding inner cylindrical surface by transmitted light. As reported previously, the pressures shattered ordinary windows of a right circular cylinder shape. Solid aluminum end plugs were used in later tests. The conical or "compression" window shown in Figure 1 was successfully tested at the maximum payload pressures of HELIUS, but plans to fabricate and test a similar design in LINUS-0 were not carried out due to the modification in the SOW.

Motion transducers (displacement and acceleration) were mounted on the rotor and movable end plate. The purpose of these motion transducers was to correlate the shock loading and end plate motion with the drive and payload pressure histories. Despite painstaking attention to mounting and cable connection, the results were inconclusive due to transducer and connector failure. Transducer internal design and connection techniques had been steadily improved as drive pressures were increased as part of the shakedown tests for the modified LINUS-0 machine. The improvements did not keep pace with the increased shock

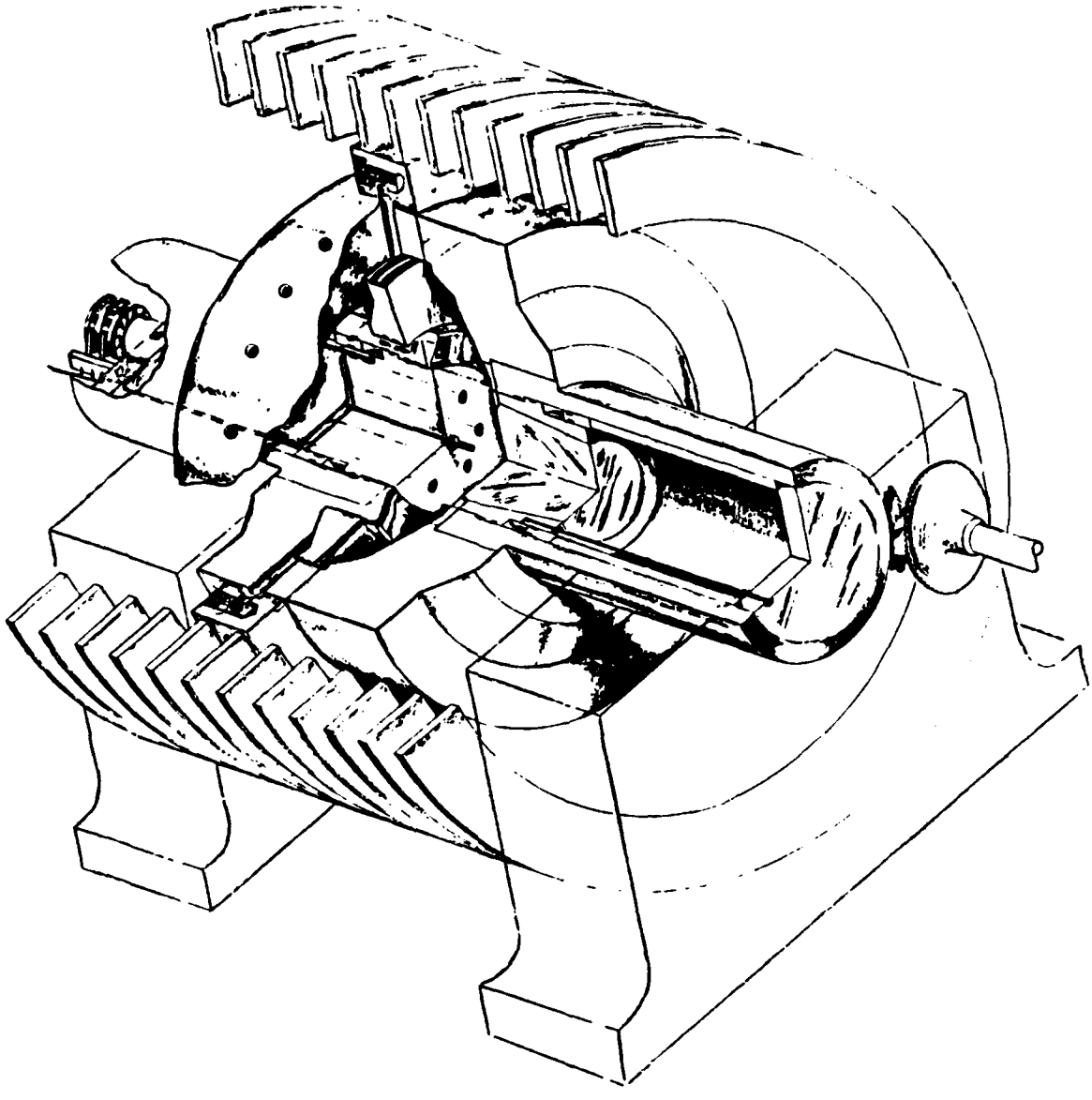


FIGURE 1. Cut away drawing of LINUS-0 showing modified piston.

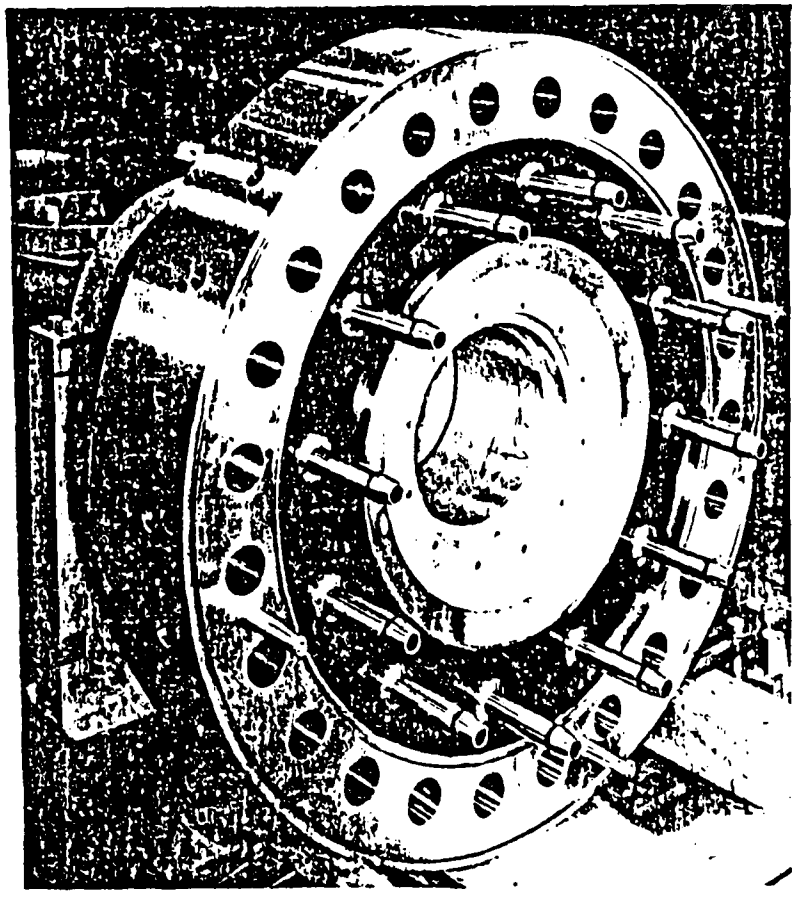


FIGURE 2. Photo of LINUS-0 rotor half with annular piston guide rods exposed.

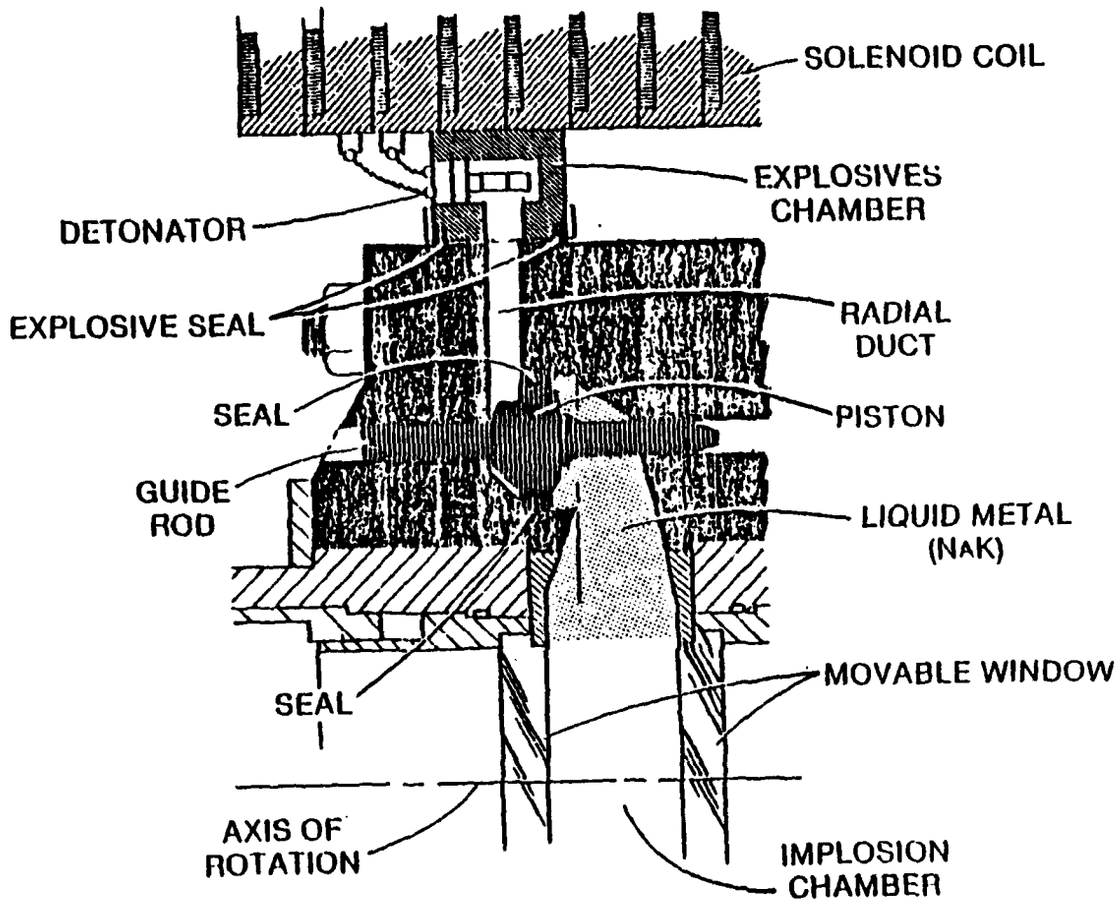


FIGURE 3. Cross-section view of LINUS-0 charge box and rotor seal areas.

loading, especially during the last testing period, where maximum drive pressures were used. Additionally, the motion transducers were only in place during this last period and due to the change in project direction at this point, no time was allowed for any adjustment or re-design. Most of the test data showed the familiar oscillographic pattern of a pressure of motion signal going off scale, sometimes returning, but most often staying off scale after a liner implosion, indicating an open circuit either internally or at the cable connection of the transducer. Although difficult to evaluate quantitatively, it seemed apparent that the "shock-absorbing" end plates did not move until after an implosion event was over. It was this inertia of the end plates, that on the rebound, caused considerable deformation to the plate outer diameter and jammed it in the rotor axle bore. The accelerometer data that was received on a few of the lower drive pressure shots was adjudged to be noise from erratic connections and so these shock histories were not subjected to the originally intended Fourier analysis. The only positive results obtained during the last testing period of LINUS-0 were produced by the drive pressure transducers mounted in the plugs of the former piston guide rod holes. The pressure histories from these transducers allowed a verification of the drive pressure history previously obtainable only by extrapolation from the charge box transducers. Such corroboration increased the confidence level in predictions obtained from the ADINC computer code that used the piston drive pressure curve as its principal initial input. One other result of note was that some improvement ($\sim$10 percent) in piston turnaround time was observed with the new piston design. With the low confidence in the recorded transducer signals, when a complete open circuit signal did not occur,it was still possible to obtain the turnaround time from the time-position of the pressure peaks. Before the disassembly and removal of the LINUS-0 and HELIUS devices actually occurred, a computer balance program was written for the HELIUS rotor so that further accelerometer testing at high rotational speeds could be done using HELIUS as a test-bed for LINUS-0.

The assembly and testing of the implosion dynamics of an already fabricated hydrodynamic model of a tangentially injected water liner into a non-rotating housing was intitated. In all previous

theoretical studies and experiments, the initial liner configuration had been created by rotating the entire pressure vessel (implosion chamber, e.g., as in LINUS-0), thus allowing the liquid to be in solid-body rotation before implosion. If such an approach is scaled up to fusion reactor sized vessels, very difficult engineering problems emerge. Design of support bearings, design of a rotary vacuum seal for plasma injection and a high pressure seal for the piston gas drive are some of these problems. The rotary vacuum seal is made even more difficult due to the enormous high pressure loading on the end plates, thus suggesting an open end wall device. The possibility of resolving these problems, caused by having to rotate the entire implosion chamber, led to an earlier test of liner formation by tangential injection of the liner fluid into a non-rotating chamber (Reference 2). If a stable inner surface could be formed in this manner, not only would it solve the problems mentioned above, but the same external pumps and exit turbines necessary to pump the liquid metal through a reactor and its heat exchange system could then be used to provide liner rotation. The initial concept was to inject and extract the liner fluid at the outer wall, in order that a thin flow layer at the outer wall would approximate solid body rotation. It was not possible to form a circular inner free surface in this manner. Instead, it was found that an untwisted, circular inner free surface could be formed by additional extraction of fluid axially through the chamber end wall, until the discharge was being equally handled radially and axially. This produced a turbulent but steady free surface of uniform circular cross section. The resulting swirl chamber is shown in Figure 4. The end wall opposite the axial exhaust parts was made of plexiglas so that flow photography was possible. The rotational speed could be measured by a strobe light illuminating 3 mm diameter styrofoam spheres which were seeded into the flow, while pressure gauges on the inlet and outer wall read source and rotational heads, respectively. Measurements allowed estimates of power losses due to viscous shear, turbulence, etc., from which a simple model based on open-channel flow was derived. This model was then used to extrapolate results to the scale of a possible LINUS fusion reactor.

The task for JAYCOR personnel was to assemble and operate a scaled-up version of the earlier swirl chamber with an attached piston

FORMATION OF LIQUID LINER BY TANGENTIAL INJECTION
(SWIRL CHAMBER EXPERIMENT)

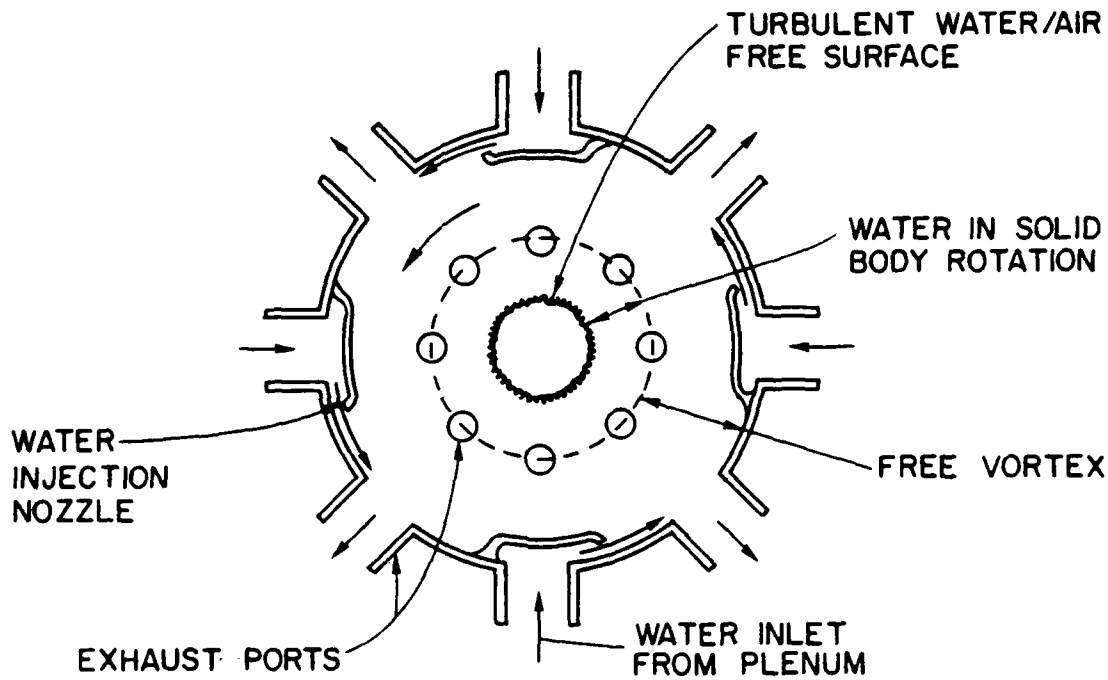


FIGURE 4. Schematic of first tangential fluid injection appratus (swirl chamber).

section so that implosion dynamics of a tangentially formed liner could be studied in addition to stable liner formation. JAYCOR engineering technicians, in conjunction with NRL personnel, assembled and operated the new swirl chamber, but the piston section, although designed, was not fabricated by the time of the SOW modification. The results of operating the new swirl chamber alone were not satisfactory, showing some trends in flow instability that had only been indicative in the earlier, small-scale version. In the larger scale swirl chamber a stable circular inner free surface could not be formed for any flow input, as a tumbling action would normally disrupt the vortex motion soon after initiation. The simple theoretical model based on open-channel shear flow and turbulent entrance and exit conditions was apparently insufficient for the scaled-up version or the free vortex. While newer, more sophisticated models were being disucussed that could suggest solutions to the unstable flow problem, the research was suspended due to the program redirection.

III. HOMOPOLAR GENERATOR/INDUCTOR POWER SUPPLY EXPERIMENTS

The subsequent change in program direction and Work Statement involved the modification, maintenance, operation and evaluation of various components of the NRL Homopolar Generator (HPG)/Inductor Power Supply. This accomplished a high power (EMP) demonstration of the power supply and a long duration, high current application for testing surge arrestors. Inductive energy storage is being developed at NRL because of its compactness and economy for high power application (10^{11} - 10^{13} W) as compared to traditional methods, such as capacitor banks (energy densities of 6-40 J/cm^3 compared to 0.04-0.25 J/cm^3). Despite their great economic advantage over large capacitor banks, inductive energy stores have not progressed as far because of problems in certain components of the inductive systems. An inductive storage system consists of three main elements: an inductor, a charging device and a switch for discharging the magnetic energy in the charged inductor. These basic components are shown in Figure 5. Unlike capacitors, a non-superconducting inductive storage coil must be charged in a short time compared to its L/R discharge time to use the energy efficiently. (L is the inductance and R the resistance of the circuit.) A pulsed charger is required. Since the charger must be rated at many megawatts in short pulses, an intermediate stage of energy storage, such as the inertial energy of a flywheel, must be used. The inertial stage's output could then be coupled to a DC generator or alternator rectifier, that would in turn provide the high current necessary to charge the inductor. To discharge the inductively stored energy then requires a high power transfer (opening) switch in order to interrupt the large currents involved and transfer, or commutate the current to the load. To achieve even higher power, further energy compressions may be necessary, i.e., discharging the energy in shorter times. This requires faster switching followed by other elements for power matching to the load to achieve high transfer efficiency and to obtain required load characteristics and performance. All of these elements of an inertial-inductive system are indicated in schematic form in Figure 6.

Although most often the components described above and indicated in Figure 6 are physically separated, as shown, these components can be combined in a novel way to produce a compact system.

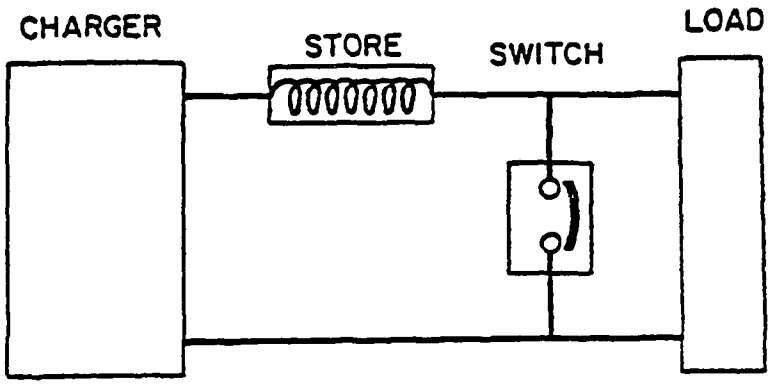


FIGURE 5. Basic components of an inductive energy storage system.

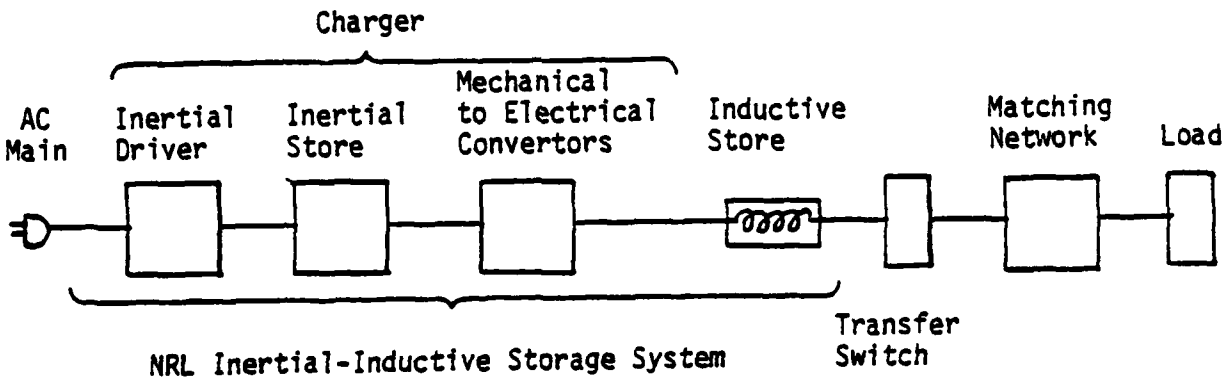


FIGURE 6. Inertial-inductive system components.

NRL not only combines the inertial driver (hydraulic motors), inertial storage (flywheel), and generator components of the charger, but also the inductive storage coil into a single unit. The unit is called a self-excited, meaning single polarity DC, hompoloar generator. The HPG is an attractive charger for an inductive store because of its high current DC output and because its rotor can also be the flywheel of the inertial storage stage. In the NRL design, the air-core inductive storage coil also acts as the excitation coil for the HPG, with the rotor or flywheel mounted inside the coil. This leads to a very compact "inertial-inductive store". Unfortunately, an HPG is a low voltage device ($\lesssim$ hundreds of volts) that must operate at very high currents (mega-amperes) to achieve the high power output required by some applications. Although the HPG is capable of delivering such high currents, a limit is imposed by the ability of opening switches to interrupt such currents and transfer energy out of the inductor to the load. The switching problem has been resolved for one parameter regime, at least on a single shot basis, by development at NRL of techniques using explosive opening switches and additional foil or wire fuse stages for further energy compression and load matching. Earlier high current opening switches (Reference 3) and switches with fast opening times were extended into the high-voltage regime (Reference 4) using a two-stage switching scheme originally investigated by Salge (Reference 5). In this scheme two switches are connected in parallel and opened sequentially. The first switch, a mechanical circuit breaker in Salge's system, replaced by an explosively-actuated one by NRL, is a low resistance device that stays closed long enough for the storage coil to be energized, and must be able to handle the large currents involved. When this switch is explosively opened, the current is diverted into the second parallel switch (the high voltage fuse) which keeps the voltage low for a short interval to allow arc extinction and voltage hold-off recovery for the first switch. This method, using fast-opening (20-30 μsec) switches, provides a means for pulse compression (steepening) by generating a large inductive voltage pulse, thereby effectively amplifying the output power of the current source. Additional pulse compression can be obtained by using a three-stage opening switch technique, with each switch in the array having a progressively shorter

opening time. This is shown in Figure 7.

The NRL HPG/Inductor Power supply was maintained, modified and operated during two recent experimental demonstrations: (1) a high power EMP demonstration requiring low-microsecond pulses and (2) a long duration (0.2 sec) high current (10 kA) test of power line surge arrestors. To provide the different outputs to meet the requirements of various user applications, test loads were coupled to the switching stages either directly or through step-up or step-down current transformers. This also provided output pulse flexibility. The high power demonstration was accomplished by utilizing a current step-up transformer to convert the 60 kA HPG/Storage Inductor current into mega-ampere currents. Results of the studies undertaken during this test phase are given in Reference 6. A typical circuit utilizing the current transformer is shown in Figure 8. Reference 7 reviews the system performance with short circuit and 1.0 MΩ loads and includes the analysis of the effects of circuit parameters on current multiplication and power transfer. Half mega-ampere currents were generated in the 1.0 MΩ load in these tests. The addition of fuse stages raised the voltage level to 200 kV. Routine operation at power levels of 10^{10} W was accomplished and scaling of these results indicates feasibility of operating the system at 10^{12} W.

In testing surge arrestor devices for power line and equipment protection against sustained high (10 kA) currents, the HPG/Inductive Storage system in Figure 8 was modified to utilize a current step-down transformer. The transformer provided an L/R time of more than 0.2 sec. Details of the transformer construction and problems encountered in its installation and operation with the surge arrestor test load are discussed in Reference 6. Testing was performed with 2.7 MJ in the inductive store, and at this level, 1 MJ was delivered to the test load. The output pulses delivered to the surge arrestor were found to depend on the behavior of a given arrestor.

During the two application test periods, in addition to providing part of the maintenance, technical modification and operation of the HPG/Inductive Storage system, JAYCOR engineering technicians performed many of the design modifications, assembly and testing of a new, simpler expolsively actuated circuit breaker (EACB) intended to

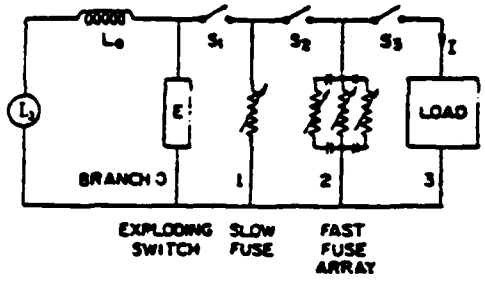


FIGURE 7. Inductive storage system with three-stage switching for high power generation.

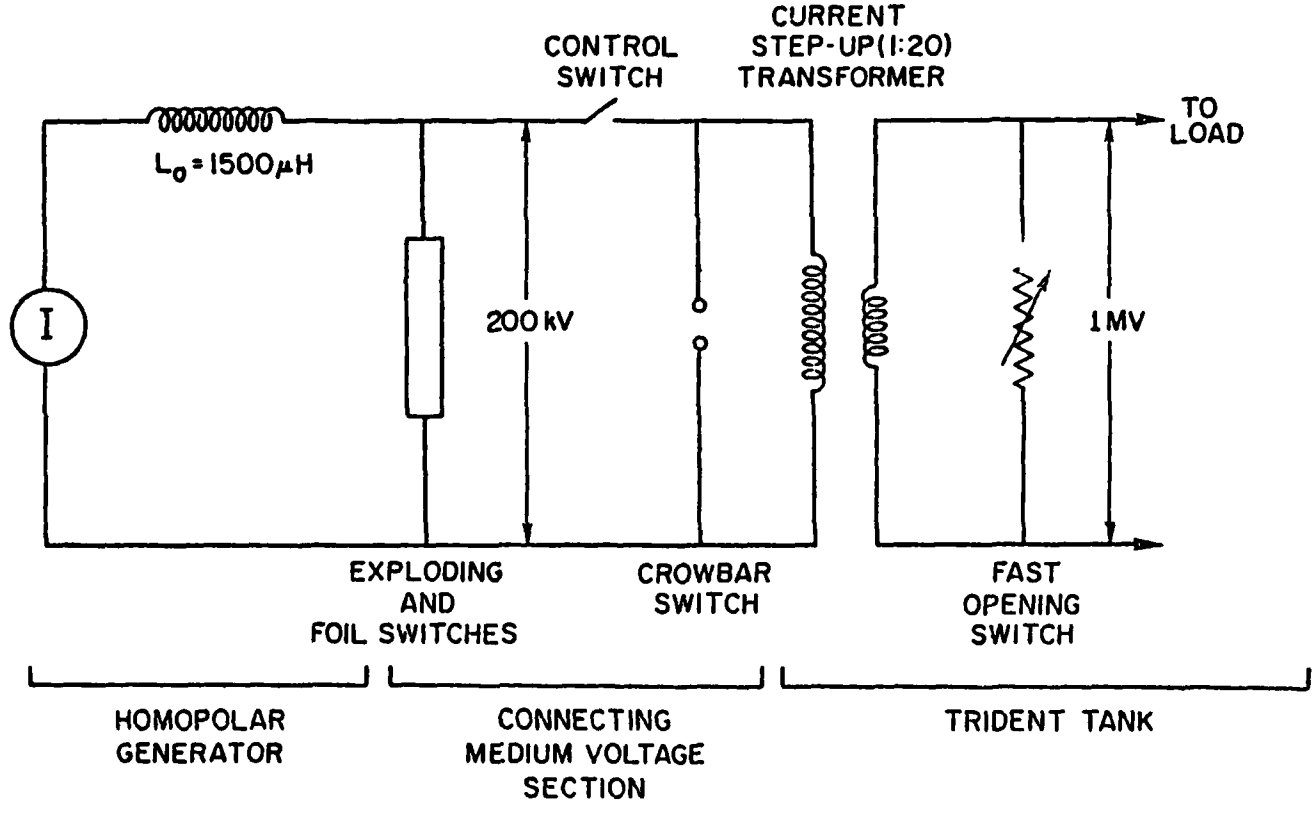


FIGURE 8. Inertial-inductive energy store utilizing a current step-up transformer for high power demonstration.

replace the present EACBs. The present EACB, discussed in Reference 3, consists of a two and one-half inch O.D. aluminum cylinder, containing the explosive charge (detonator cord) on axis surrounded by paraffin, with an alternating series of steel and polyethylene rings surrounding the tube. The aluminum tube provides the low-resitance, long-duration path for the high current. When the explosive is detonated the paraffin is driven against the inside wall of the aluminum tube, which is ruptured at the steel cutter ring edges on the outside of the tube. The ruptured aluminum splits along axially scribed lines and folds around the radial edge of the bending rings, thereby forming a series of insulating gaps, with the flowing paraffin helping to cool and extinguish the arcs in the gaps. Although the EACBs just described have given good, reliable performance in the past, a new design, shown in Figure 9, is believed to be simpler to fabricate and assemble. It may provide even more reliability and consistency of operation and is expected to give longer current carrying capability, with four times the arc voltage and six times the recovery voltage of the above cylindrical switch. In initial tests a switch arc voltage of 2 kV/cm was obtained. The single-gap switch interrupted a linear current density of 2 kA/cm in about 10 μ sec with a recovery field of 100 kV/cm achieved at 25 μ sec after interruption. It is hoped that the switch can carry currents at the 50 kA level for long ($\sim$ 1 sec) times associated with HPG charging systems.

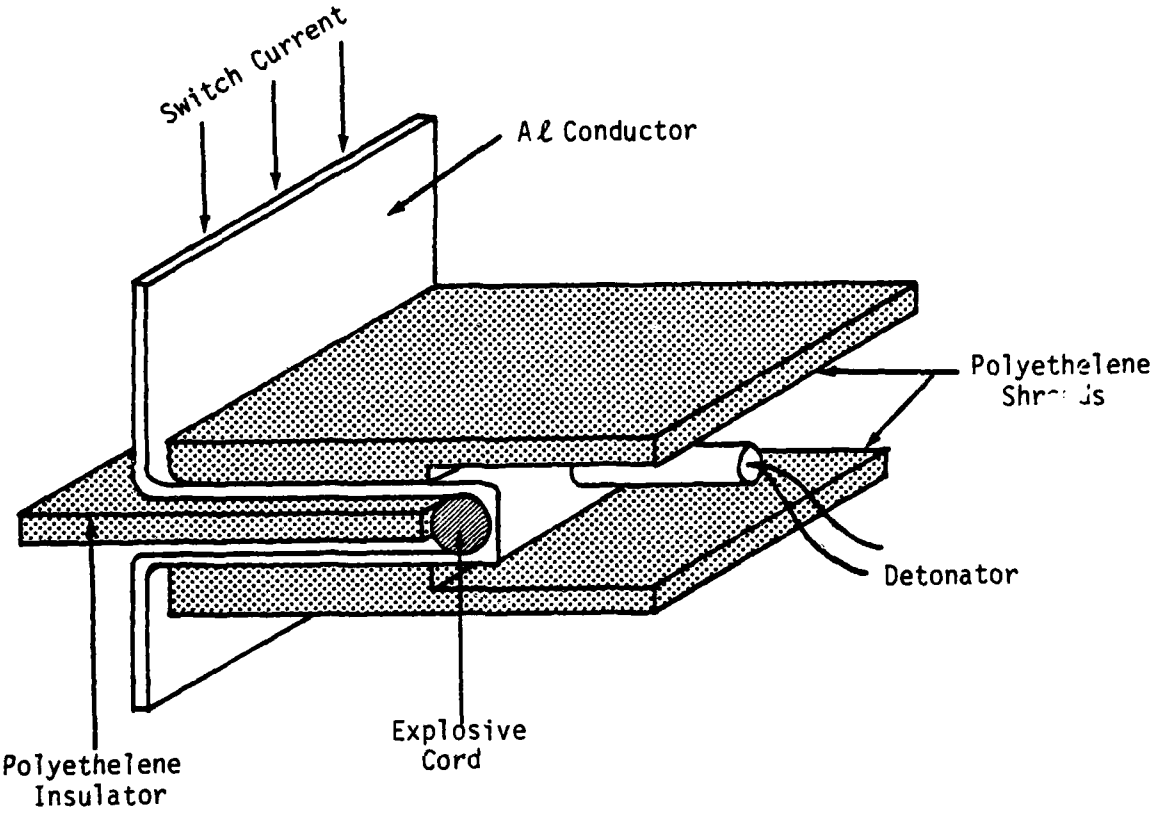


FIGURE 9. Simple, explosively-actuated circuit breaker (EACB).

IV. PLASMA SWITCH EXPERIMENTS

The design, assembly and testing of various components of the NRL plasma switch experiment was accomplished. Opening switch technology represents one of the difficult problem areas in utilizing inductive energy storage for high power applications. This is especially true if repetitious switching is required by the application. Although the explosive switches, e.g., EACBs, foils, have been very successfully operated in a sequential or parallel-ganged mode, a single rapid opening and closing switch that could operate at a reasonable repetition rate and that would not have to be replaced after each opening action is highly desirable. Unfortunately, at the high power and current levels required by certain applications, such a switching task is extremely difficult. One possible repetitive high power switch that has been proposed is the plasma switch using plasma guns as the plasma source (Reference 8). The operation of the plasma switch is shown schematically in Figure 10. Its principle is based on the use of dense plasma flow (10^7 - 10^8 cm/sec) generated by an external plasma gun. When the plasma is flowing through the electrode gap region shown in Figure 10, it will support the conduction of high currents between the electrodes. As the plasma exits the gap region, conduction ceases and the current is interrupted. This switch has the potential to combine high current capability with fast opening and recovery time, as well as high hold-off electric fields.

The JAYCOR effort was mainly involved with the design, assembly and testing of various components of a plasma switch system provided by NRL in conjuction with the exploratory experiments performed under JAYCOR contract N00014-81-C-2152. The original plasma deflagration gun plasma source, shown in Figure 11, proved to give unsatisfactory performance and had to be modified. Before testing was started with the plasma gun, a test stand and cradle for the vacuum system had to be designed, fabricated and assembled. The oil diffusion pump was disassembled, cleaned, and reassembled. The vacuum system required the design and fabrication of adaptor flanges and instrumentation access flanges.

The parts of a deflagration plasma gun had been previously fabricated from drawings based on a gun obtained from Internationl Power

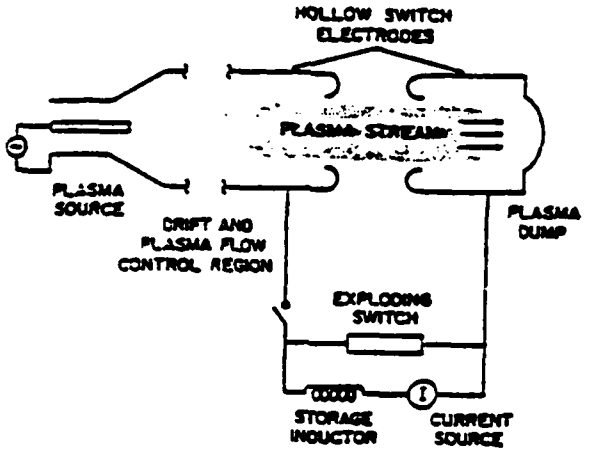


FIGURE 10. Schematic configuration of plasma switch operation.

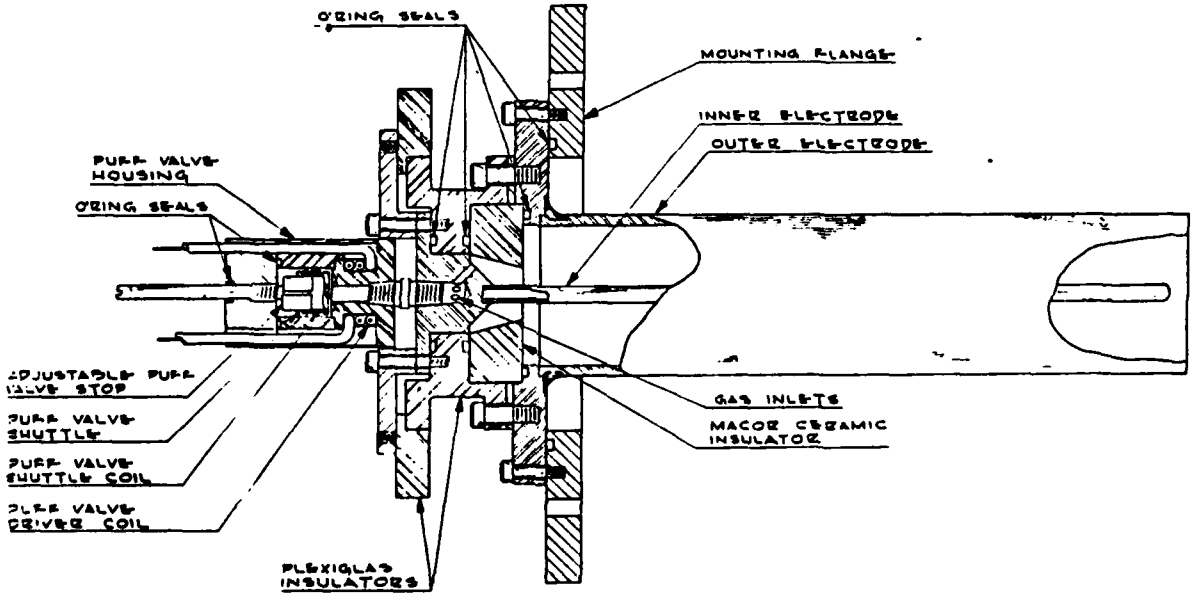


FIGURE 11. Plasma deflagration gun.

Technology Inc. Upon inspection of the parts, several design flaws were noted, particularly to the puff-valve assembly. These parts were redesigned and fabricated.

Once the necessary components were available, the plasma gun, the test stand, cradle and vacuum system were assembled. The puff-valve triggering mechanism was redesigned to allow remote operation. The puff-valve required several additional modifications before the plasma gun would operate repetitively. The shuttle was redesigned with more clearance in the housing and to accommodate larger diameter wire in the coil. The shuttle stop was modified to give more area for gas flow.

For diagnostics, a housing and adjustable lens system was designed and fabricated for use with a photomultiplier tube. Also, 2.5 cm diameter and 5 cm diameter aperture plates were designed for use in the system. An electrode assembly for the plasma switch which is adjustable in length and spacing was designed.

V. CONCLUSIONS

Experiments on LINUS-0 and HELIUS to determine impulse loading using pressure, motion and acceleration transducers and on a scaled-up swirl injection chamber for use on implosion studies of a tangentially injected water liner were largely unsuccessful. In both cases, the efforts were in their initial stages, despite being chronologically near the half-way point in the contract. Design, fabrication and assembly stages occupied most of this period. Due to the change in direction of the LINUS program at this juncture, no time was allowed to try new modifications or techniques to rectify the problems encountered.

Experiments on applications of the NRL HPG/Inductive energy store, however, were successful, with JAYCOR contributing to the various modifications and test operations, especially to the development of a new simpler explosively actuated circuit breaker. JAYCOR efforts in the start-up phase of the NRL plasma switch experiment involved design, assembly and testing of various system components, especially the vacuum system and plasma gun source. This experiment is still in the initial shake-down phase and results are not available at this time.

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